Flywheel Technology Development Program for Aerospace Applications

David A. Christopher and Raymond Beach
NASA Lewis Research Center

ABSTRACT

An overview of advanced flywheel development for energy storage in aerospace applications is presented. The advantages offered by this emerging technology are described and the current NASA approach toward developing the technology is presented.

KEY WORDS

Energy Storage, Flywheel, Power System, Attitude Control, Power Peaking, Load Leveling

INTRODUCTION & BACKGROUND

Development of advanced flywheels began in the 1970s following the oil embargo and gas crisis. Interest in flywheel systems development occurred after publication of several papers that quantified the benefits of an advanced system that would utilize composite materials and high speed bearings to build a system called a "super-flywheel." The Energy Research and Development Agency (ERDA), and later the Department of Energy (DoE), funded flywheel system development for a number of applications including a "super-flywheel" for an electric vehicle. The Lewis Research Center, through NASA funding in support of ERDA, was involved in the development of mechanical bearings to be used in a vacuum, and transmissions for flywheel systems to be used in a hybrid vehicle. NASA also funded research work in the area of magnetic bearings for spacecraft momentum wheels at the Goddard Space Flight Center (GSFC).

During the 1980s funding for flywheel energy research was curtailed at the DoE, but further work by NASA continued in support of satellite flywheel systems. Work on magnetic bearings continued at GSFC [1] and work on flywheel momentum configurations and combined energy storage and attitude control was done at Langley Research Center [2] (LaRC) and Marshall Space Flight Center (MSFC), respectively. The NASA work during this period was funded at a low level, primarily focused on research, but did evolve into full working systems at GSFC and MSFC.

Advances in recent years of high strength/lightweight composite materials, high performance magnetic bearings, and power electronics technology has spurred a renewed interest in flywheel energy storage (FES) technologies, not only for spacecraft applications, but also in the transportation, utility, and manufacturing industries.

Flywheels promise order of magnitude increases in performance and service life in many NASA applications including spacecraft, launch vehicles, aircraft power systems, uninterruptable power supplies, and planetary rovers. The NASA Lewis Research Center (LeRC) effort is aimed at both developing working flywheel

Authors' Current Addresses:
D.A. Christopher, NASA-Lewis Research Center, Power & Propulsion Flight Projects Office, Mail Stop 301-5, 21000 Brookpark Road, Cleveland, OH 44135-3191, USA; and R. Beach, NASA Lewis Research Center, Power Technology Division, Mail Stop 301-5, 21000 Brookpark Road, Cleveland, Ohio 44135-3191, USA.

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systems and advancing the supporting technologies. The work is accomplished through partnership and cooperative arrangements with industry and other government agencies.

NASA APPLICATIONS & BENEFITS

It can be useful to loosely categorize flywheel applications as serving either energy storage or peak power requirements, although there can be considerable overlap between these categories. Energy storage applications are driven primarily by a demand for high specific energy. This requirement drives designs to the highest possible rotor speeds with commensurate demands upon the rotor structural design and magnetic bearing operating speeds. Peak power applications, on the other hand, stress quick response to rapid and large increases in loads. This requirement stipulates the use of a large motor/generator and places a premium on understanding and controlling dynamic interactions between the motor/generator, rotor dynamics, and magnetic bearing controls. NASA applications fall into both energy storage and peak power categories as well as a combination of the two.

Potential space applications fall primarily into the energy storage category. They encompass the range of vehicles from small satellites and probes to manned space stations. Low earth orbiting (LEO) satellites, in particular, can benefit from this technology because of the large number of charge/discharge cycles they experience. FES benefits include dramatic savings in cycle life, weight, efficiency, maintenance, cost, and logistics.

In spacecraft a significant benefit can be gained by combining energy storage with attitude control functions. Flywheel-based Integrated Power and Attitude Control Systems (IPACS) are highly supportive, and in some cases, enabling for current NASA and industry goals of devising lighter and lower cost spacecraft while retaining significant capability. Commercial companies are extremely interested in this innovative technology to help retain their competitive advantage over foreign firms.

The promise of flywheel-based IPACS technology is dramatically revealed by comparing this new technology with current generation spacecraft using the key metric of specific energy. Figures 1, 2, and 3 provide the specific energy values as calculated at the battery level, energy storage system level, and the spacecraft level for three current generation spacecraft of various sizes: a small spacecraft (~300 W power bus); a mid-sized spacecraft (~2kw bus); and the International Space Station (ISS, > 9kW bus). The specific energy at the battery level includes the battery cells, battery wiring and diodes, and support box. The energy storage system level calculation adds in electronics for battery charge/discharge and bus regulation, and solar array over-sizing for taper charge. At the spacecraft level, the mass of the attitude control system is also accounted for.

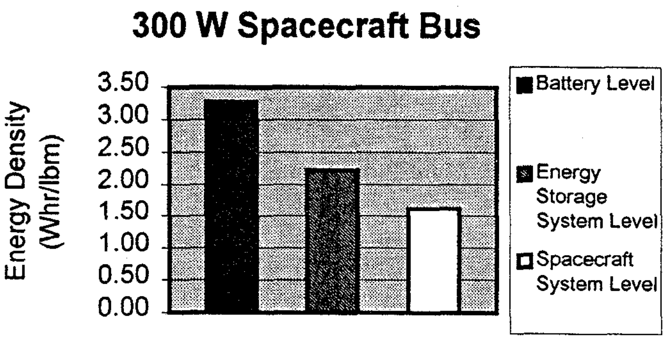

Fig. 1. Small Spacecraft Specific Energy

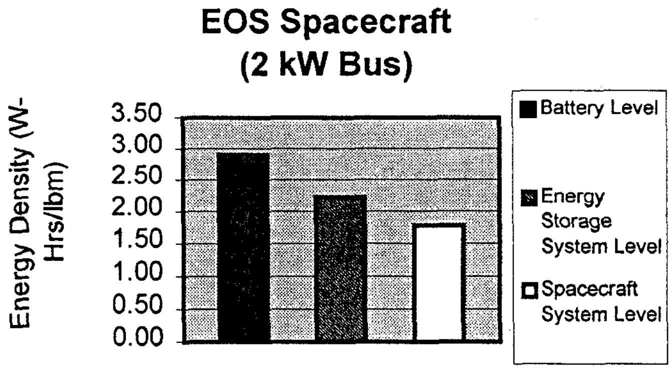

Fig. 2. Mid-Sized Spacecraft Specific Energy

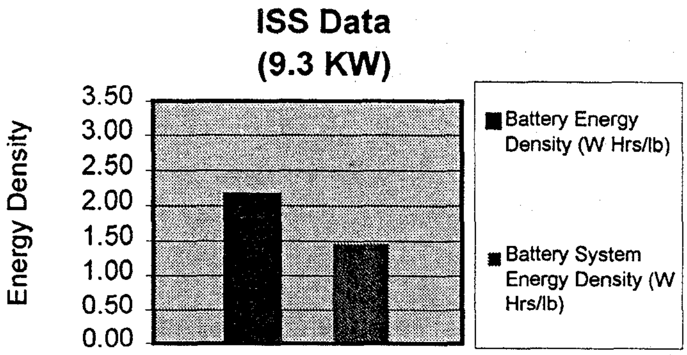

Fig. 3. Specific Energy for a Large Spacecraft

The specific energy at the spacecraft level is perhaps surprisingly low at around 1.5 Whr/lb. This is because the calculations includes system masses that are often overlooked. For example, the mass of electronics for battery charge/discharge and bus regulation, solar array area oversizing for taper charge, and the attitude control system are included.

These calculations only include the nominally used energy (i.e., energy available down to operational depth-of-discharge (DOD)).

For comparison, specific energies as high as 20 WHr/lbm are predicted for first generation IPACS. Figure 4, on next page, provides some insight into how IPACS technology will achieve such dramatic gains. This chart reveals that the major contributors to the high specific energy of flywheel systems are deep nominal DODs and

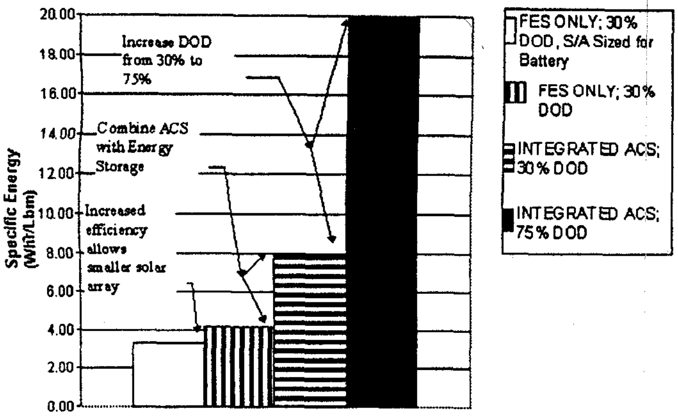

Fig. 4. Characterization of Flywheel S/C Benefits

the ability to combine attitude control system (ACS) and energy storage functions into a single set of hardware.

A couple of points are worth noting. First, is that the nominal DOD for a flywheel system is a function of motor/generator trade-offs (e.g., efficiency, sizing) rather than a lifetime issue. Motor/generators are sized for nominal power levels within the nominal power range, but reduced power can be provided all the way down to 0% DOD in off-nominal situations. The second point to note is that the projected 20 Whrs/lbm is based upon derating flywheel systems that are currently under development in the laboratory and being designed to reach over 80Whrs/lbm. The calculation is based upon a 4-flywheel IPACS system, includes power conditioning and control electronics, and assumes a DOD of 75%. No attempt was made to include secondary benefits to thermal and structural subsystems or loads.

These comparisons reveal that the advantages of FES derive as much from affects on the system as from performance gains inherent in the technology. Potential FES applications are listed in Table 3.

In fact, there are many other benefits beyond those already mentioned that will be of interest to spacecraft mission and hardware designers. Tables 1 and 2 summarize both energy storage and attitude control function benefits projected for integrated power and attitude control systems.

Potential power peaking, or load leveling, applications can be found in launch vehicles (LVs), aircraft power systems, and other terrestrial uses. Next generation launch vehicle or upgrades of current LVs could benefit from using flywheels as load leveling devices. This could be especially beneficial for systems which use fuel cells for energy generation, otherwise the fuel cells must be sized for peak loads. Flywheels are synergistic with the use of electro-mechanical actuators (EMAs) or electro-hydrostatic actuators (EHAs) in launch vehicles by serving as the power system equivalent of an hydraulic actuator. A similar role is seen for flywheels in aircraft power systems as aircraft manufacturers also seek to replace hydraulic systems with EMAs or EHAs. Commercial ventures would like to use flywheel based IPAC systems to handle the power peaking demands inherent to the LEO communication satellite constellations on the drawing boards.

Table 3, on next page, also lists power peaking, or load leveling, applications that are foreseen.

Table 1.

Electric Power System(EPS) Advantages	
Energy Storage Characteristics	**Resulting Benefits**
5-10+ times greater specific energy	Lower mass
Long life (15 yr.) unaffected by number of charge/discharge cycles	Reduced logistics, maintenance, life cycle costs and enhanced vehicle integration
85-95% round-trip efficiency	More usable power, lower thermal loads, compare to <75% for battery system
High charge/discharge rates & no trickle charge required	Peak load capability, 5-10% smaller solar array
Deterministic state-of-charge	Improved operability
Inherent bus regulation and power shunt capability	Fewer regulators needed, e.g., could eliminate solar array shunt regulator

Table 2.

Attitude Control System (ACS) Advantages	
Attitude Control Characteristics	**Resulting benefits**
Long life	Reduced logistics, maintenance, and life cycle costs
Large control torques	Reduced propellant needs (wheels can now handle requirements that previously demanded prop systems)
Large momentum storage capability	Reduced propellant needs (flywheels can handle requirements that previously demanded prop systems)
Magnetic bearing suspension reduces vibration	Improved sensor payload performance, and microgravity environment

Table 3.

Potential Applications by Category	
Energy S torage	**Load Leveling**
• LEO satellites • GEO satellites • Space Station • Planetary probes • Aircraft • Military vehicles • Hybrid and electric vehicles • Uninterruptable Power Supplies (eg., KSC launch operations)	• Spacecraft with peak loads • Shuttle upgrades • Advanced launch vehicles • Aircraft • Military vehicles • Hybrid and electric vehicles • Electric vehicle charging stations • Pulsed Power Devices

PROGRAM PLAN

The maturity of the technology (See Table 4) has led us to focus efforts first on spacecraft applications. A two-pronged approach is developing flywheel systems in parallel with validating, advancing, and maturing the component technologies. Technology efforts complement the system development work and vice versa.

FLYWHEEL SYSTEM DEVELOPMENT

Efforts are underway to develop flywheel systems for large, medium, and small size spacecraft. The large wheel sizes benefit from "economies of scale" and have a higher level of maturity.

NASA is teamed with the USAF Phillips Laboratory to develop a multi-wheel system that demonstrates the integration of energy storage and attitude control functions. The contract was awarded to SatCon in December 1996 under the Small Business Technology Transfer Program (STTR). Objectives include design, fabrication, and test of a prototype multi-wheel IPACS, including associated electronics, in just over two years. The system will be tested to typical spaceflight hardware environmental qualification levels at NASA LeRC. Extensive tests are planned to verify power and attitude control performance both independently and simultaneously. Project requirements were crafted to encompass as wide a range of potential NASA and USAF LEO missions as practical. A parallel effort to design a high performance rotor based upon polar weave composite structure technology provides the potential for a future performance upgrade. This parallel task is being conducted by Dow-UT under coordinated sponsorship with the Office of the Secretary of the Air Force.

In a separate effort, NASA contracted with TRW in mid-1996 for an engineering model fidelity FES system.

Table 4.

Technology Assessment by Application	
Application	**Key Remaining Challenges**
Large LEO spacecraft (>5 kW bus)	• Specific energy > 20 whr/lbm • Life > 50,000 charge/discharge cycles • Safety • Torque & momentum control • Integration of power & ACS functions
Mid-sized LEO spacecraft (1-5 kW bus)	• Specific energy > 20 whr/lbm • High rpm (90,000 +) • Life > 50,000 charge/discharge cycles • Safety • Integration of power & ACS function
Small LEO spacecraft (<1kW bus)	• Feasibility of flywheels smaller than ~200 Whr at acceptable specific energy
GEO spacecraft	• Specific energy > 40 whr/lbm • Low parasitic losses • Safety • Integration of power & ACS functions
Advanced Launch Vehicles (or Shuttle upgrade)	• Mag bearing & motor/generator interactions • Safety
Aircraft	• Mag bearing & motor/generator interactions • Containment • Moderate unit cost.
Terrestrial applications	• Very low unit cost • Containment

TRW is acting as system integrator on this task and has sub-contracted the flywheel development to US Flywheel Systems, Inc. The purpose of this effort is to begin down a path that will lead to mid-size flywheels (on the order of a few hundred watt-hours energy storage). This first system is derived from designs for terrestrial applications and will store about 1 kW-hr per wheel. Its purpose is to obtain early hands-on experience with working flywheel systems prior to proceeding to spaceflight flywheel designs. System objectives include demonstrated control of two flywheels to store energy with zero net momentum generated and to produce commanded single axis control torques. The total specific energy of the delivered system is anticipated to be as high as 20 W-hrs/lbm for this non-optimized design. After initial checkout at TRW, the system will be delivered to NASA LeRC in late 1997 for extensive characterization testing.

A third system development effort is targeted at investigating small flywheel feasibility. FARE, Inc., under a NASA Small Business Innovative Research (SBIR) Phase II contract, is developing a 50 W-hr laboratory unit [3]. This two-year effort is scheduled for completion in early 1999.

A first flight demonstration opportunity has been awarded under the International Space Station (ISS) as an Engineering Center (ISSEC) program. NASA LeRC has teamed with the USAF, the NASA Johnson Space Center, Boeing, and Oak Ridge National Laboratory to launch a flight experiment to the ISS in the late 2000/early 2001 time frame. The flywheel design and supplier has not yet been selected. The experiment objective is to demonstrate, on-orbit, FES as well as a building block capability for an IPAC system. An extra benefit of this flight opportunity will be to show the feasibility of an option to replace NiH_2 batteries with flywheels as they wear out. The experiment will install a counterrotating pair of flywheels (two wheels total) as a "plug-and-play" substitute for a single battery and its charge/discharge control unit. The unit will operate in parallel with two NiH_2 batteries on one of the ISS primary power channels.

TECHNOLOGY PLAN

Efforts to develop flywheel systems require attention to numerous support disciplines and component technologies. Forlunately, significant synergism with other efforts are possible. Examples include the magnetic bearing and composite materials work being pursued in support of gas turbine engines. Of course, it's not a completely free ride. A technology developed for one application requires tailoring to fit another. The following paragraphs describe how NASA is actively endeavoring to translate advances in key component technologies into flywheel systems. In addition to improved performance, goals are to increase the reliability, lifetime, and especially the safety of flywheels. As flywheel systems are developed and demonstrated, the future of NASA technology efforts will be to focus almost exclusively on further improvements in flywheel performance via further gains in these technologies.

Bearing Systems

Flywheels require bearing systems comprised of magnetic bearings and mechanical bearings that work in concert. Magnetic bearings provide long life, low losses, and dynamic control during normal operations [4]. They are one of the keys to achieving high specific energies. Mechanical bearings provide the capability for operations through the launch environment and as touchdown bearings during contingencies.

Magnetic bearing technology in particular has recently seen considerable development by industry, NASA LeRC, and others for use on gas turbine engines for aircraft and other applications. These developments are largely applicable to flywheel systems for high speed (DN), low loss, high reliability designs. Development testing is planned at NASA, Texas A&M University, and the University of Virginia. The Center for Space Power at Texas A&M is developing three dimensional models of magnetic bearings to aid in the design of future, higher rpm bearings.

Materials and Structure

High performance composites are a second enabling technology for advanced flywheels with high specific energies. Flywheels will benefit directly from the continuing development of higher strength fibers for composite materials. Design of high speed rotating composite structures can benefit from the design tool development for composite structures for turbomachinery such as jet engine compressors. NASA will perform analyses, coupon tests, and rotor tests to assure safe, reliable, high performance designs.

Power Electronics

The power electronics provide charge/discharge and power conditioning functions. The electric machine, i.e., motor/generator, provides inherent capabilities that need to be developed, such as power shunt capability. In addition, with the long life anticipated in the mechanical components of flywheels, the life of the power electronics could become the limiting factor. The efficiency and reliability of power electronics has improved steadily in the last two decades. The challenge for flywheel designers is to incorporate these and future advances and then to successfully integrate the flywheels into the power systems. NASA space power testbed facilities will greatly aid in this aspect of the development work.

System Integration

It was observed earlier that the benefits of flywheels in spacecraft applications occurs largely at the system level. It is critical that attention be directed to this during the development phases. To assure that this occurs, system designers, such as TRW, Boeing, and NASA mission centers (e.g., GSFC, JSC) are deeply involved in the development efforts. NASA is also conducting system analyses and studies to help guide the work.

Safety and Reliability

Safety concerns remain to be addressed in every application area. NASA is coordinating with a DARPA program which is aimed at characterizing flywheel rotor burst events with the goal of preventing and containing them. This DARPA program will provide an important database from which flywheel designs can be assessed. NASA safety, reliability and quality personnel are actively involved in our system development and technology efforts to help address safety concerns early in the process. TRW is under contract to NASA to produce an early FMEA to ensure that no critical areas are being overlooked.

CONCLUSION

Successful development of flywheels including integration into flight spacecraft systems will pave the way for other aerospace uses, such as aircraft and launch vehicles, followed by terrestrial applications. Potential terrestrial applications include UPS systems and electric or hybrid vehicles and represent huge potential commercial markets beyond the aerospace industry. NASA is working closely with industry and other government agencies in a holistic approach to developing flywheel systems in parallel with a comprehensive approach to validating, advancing, and maturing the component technologies.

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